LCLS Stability Studies

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Introduction

- Sensitivity analysis to confirm and extend previous results.
- Simulation of variation in accelerator and FEL performance.

- Use the LCLS lattice developed by P. Emma and M. Woodley.
- Track from 150 MeV point with particle file provided by P. Emma (1 μm slice emittance).

Simulation Code

- Use 6-D tracking code **elegant**.
- Physical effects included:
  - 2nd-order matrix tracking.
  - RF elements with exact time and energy dependence, and end-focusing.
  - Transverse and longitudinal wakefields of accelerating structures.
  - Resistive wall wakefields.
  - Incoherent synchrotron radiation.
  - Slice-based FEL evaluation (M. Xie’s formulae).
  - Variation in phase due to variation in energy in upstream chicane.
- CSR is included in BC2 and DL2 in some runs.

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Importance of Slice Properties

- Beam is chopped into 20 longitudinal slices for analysis.
- FEL performance from average over slices is better than whole-beam results.
- This advantage is even greater in the presence of errors.
- “Core slices” (central 80%) are used consistently in all analysis

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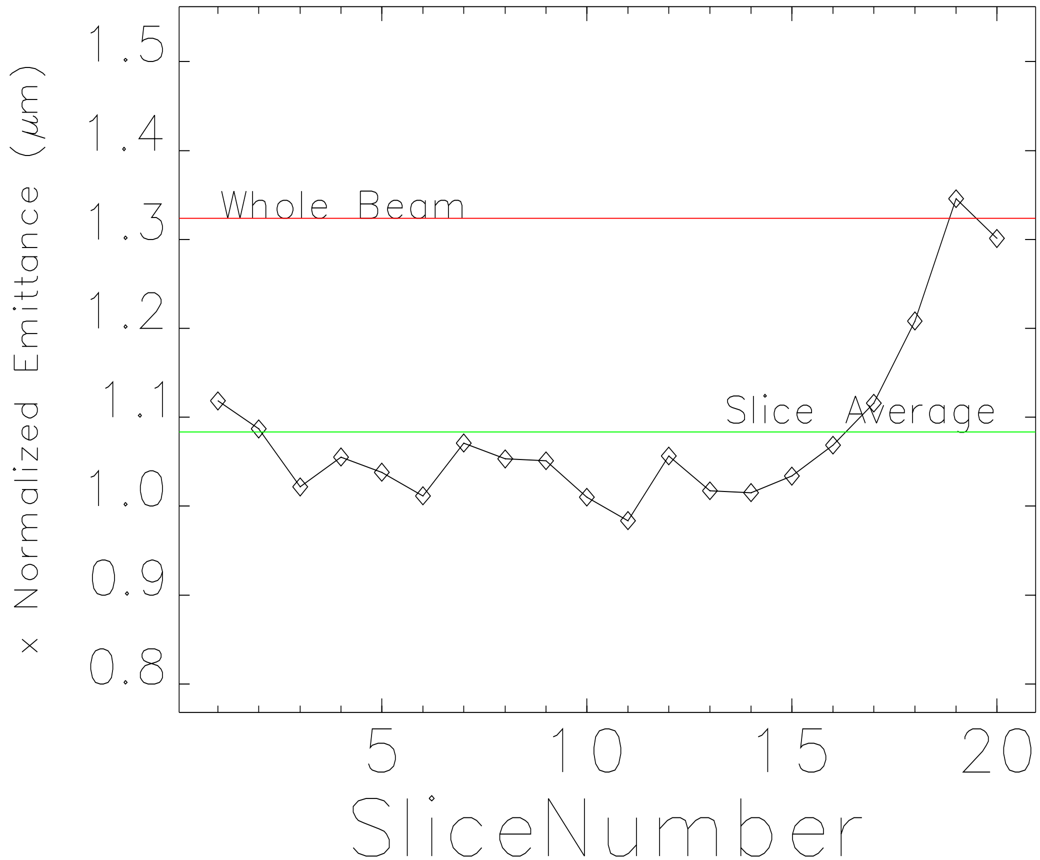
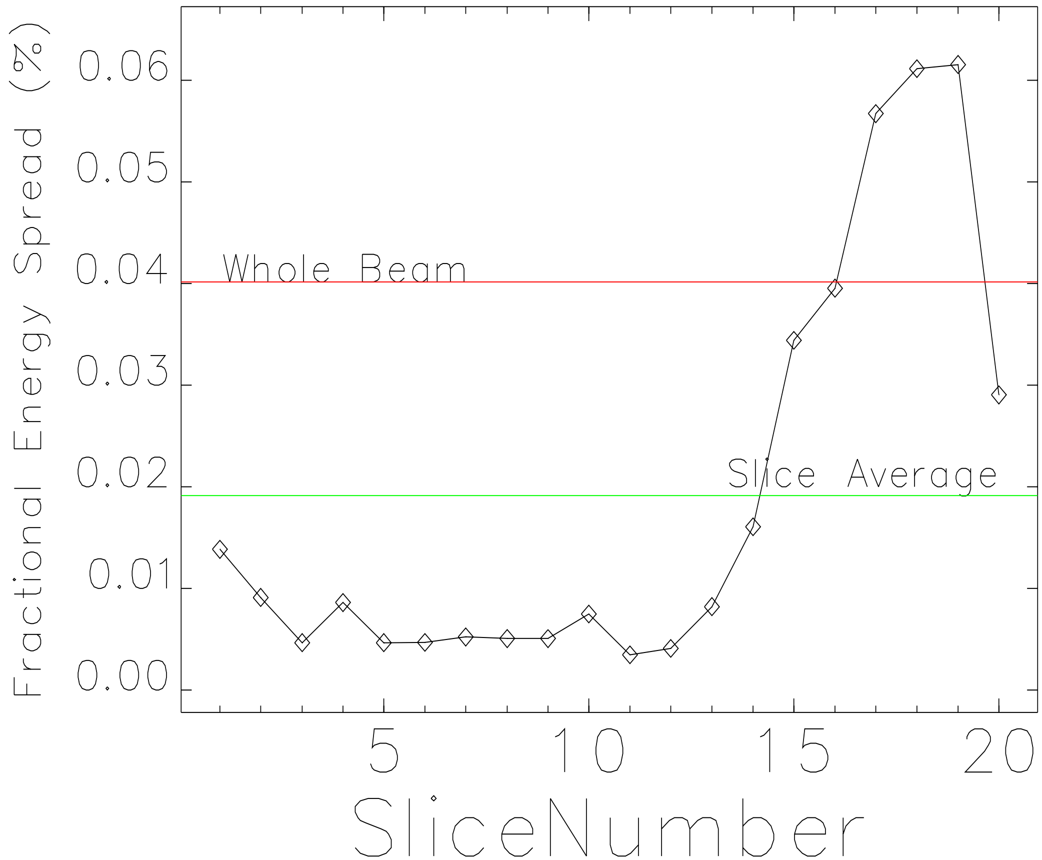
Slice Computation of Emittance



Slice Computation of Energy Spread



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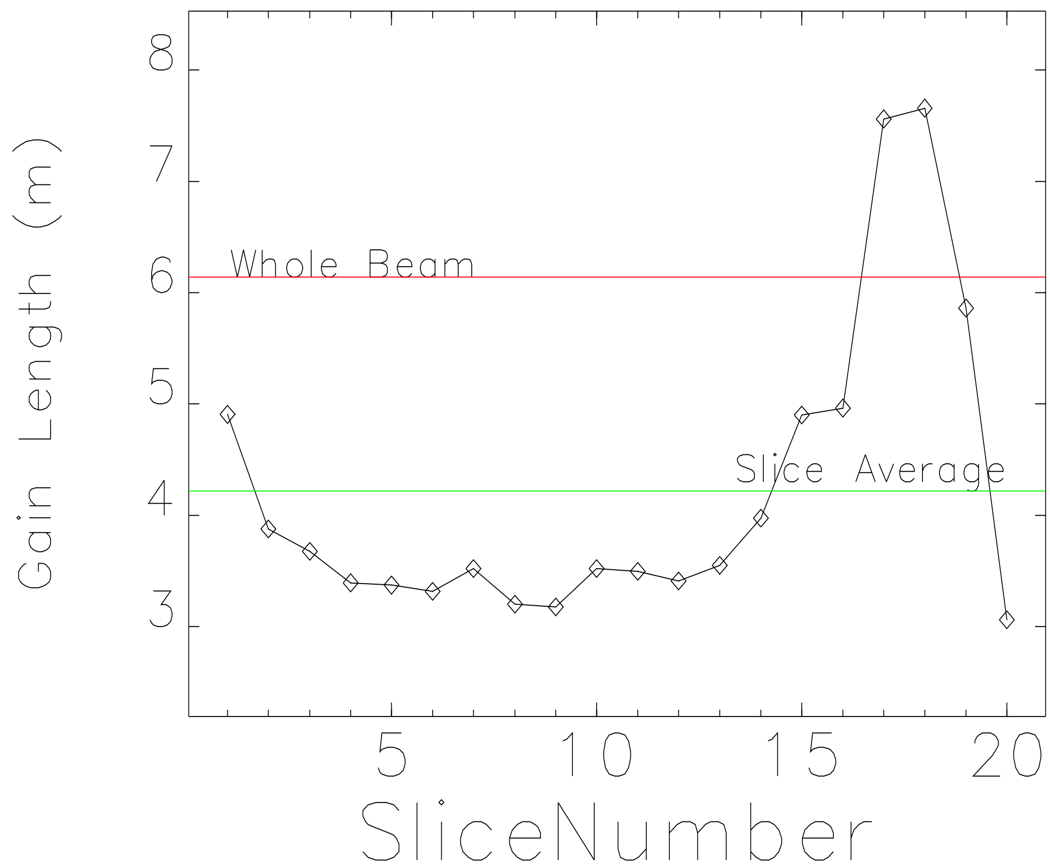
Slice Computation of Gain Length



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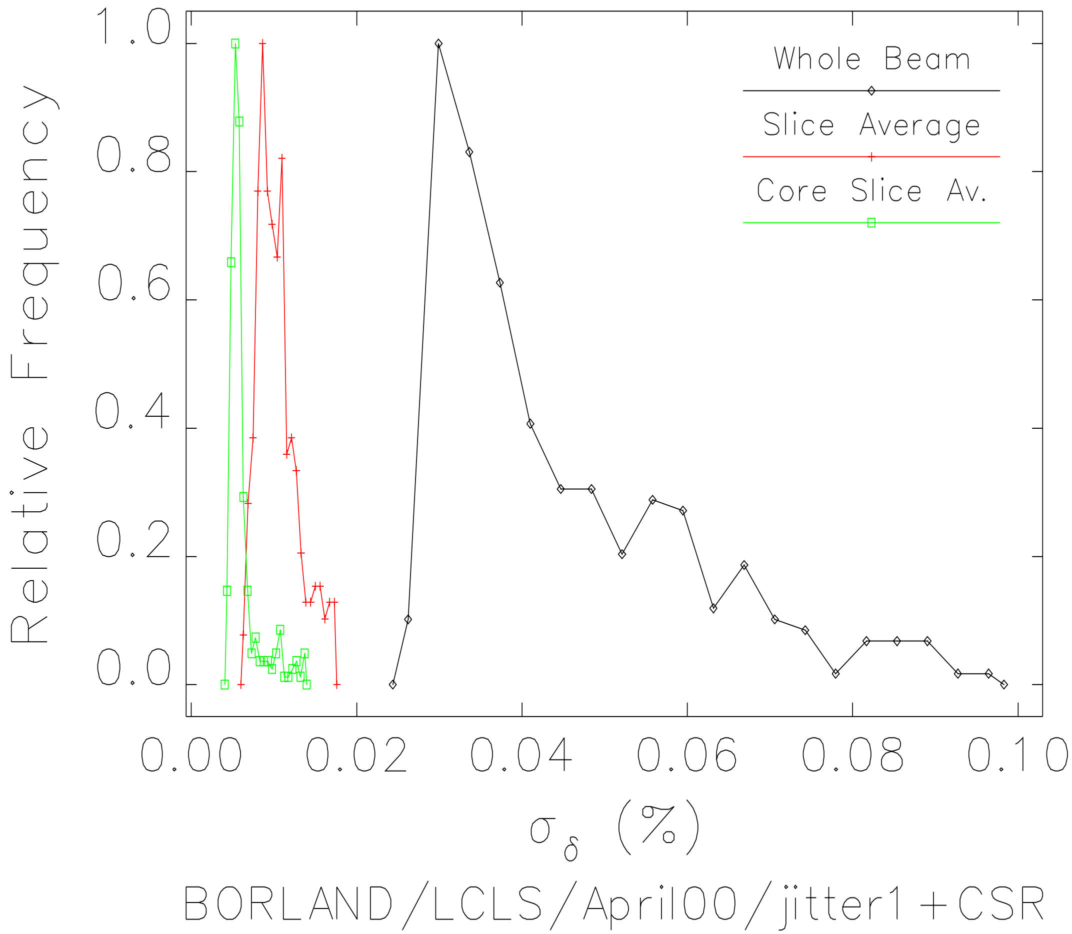
Preview of Jitter Results



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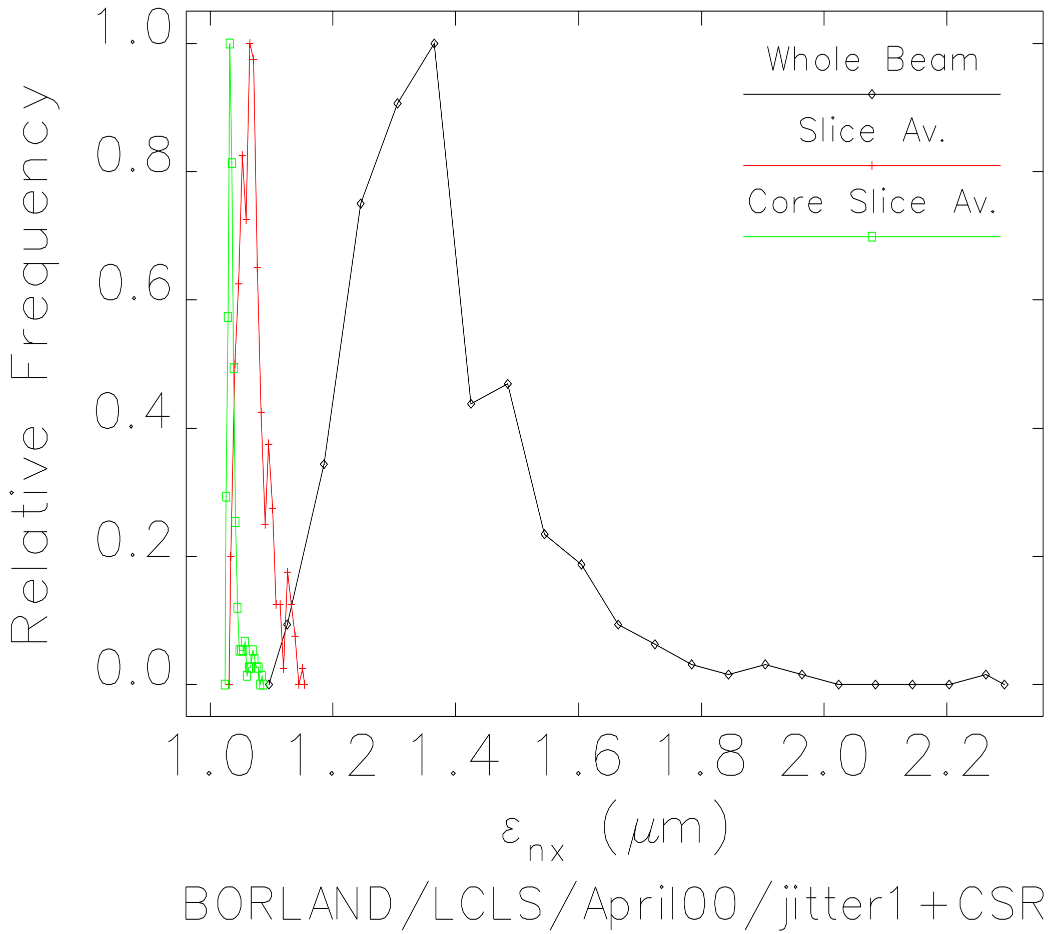
Preview of Jitter Results



Energy Tail

- The low-population high-energy tail in the beam tends to throw off calculations.
- A “calculational cut” is used that removes most of this tail (top 1%).
- In reality, energy slits in the bunch compressors are not advisable:
    - RMS energy centroid jitter is ~50% of the RMS energy spread.
    - Slits would therefore result in substantial intensity jitter.

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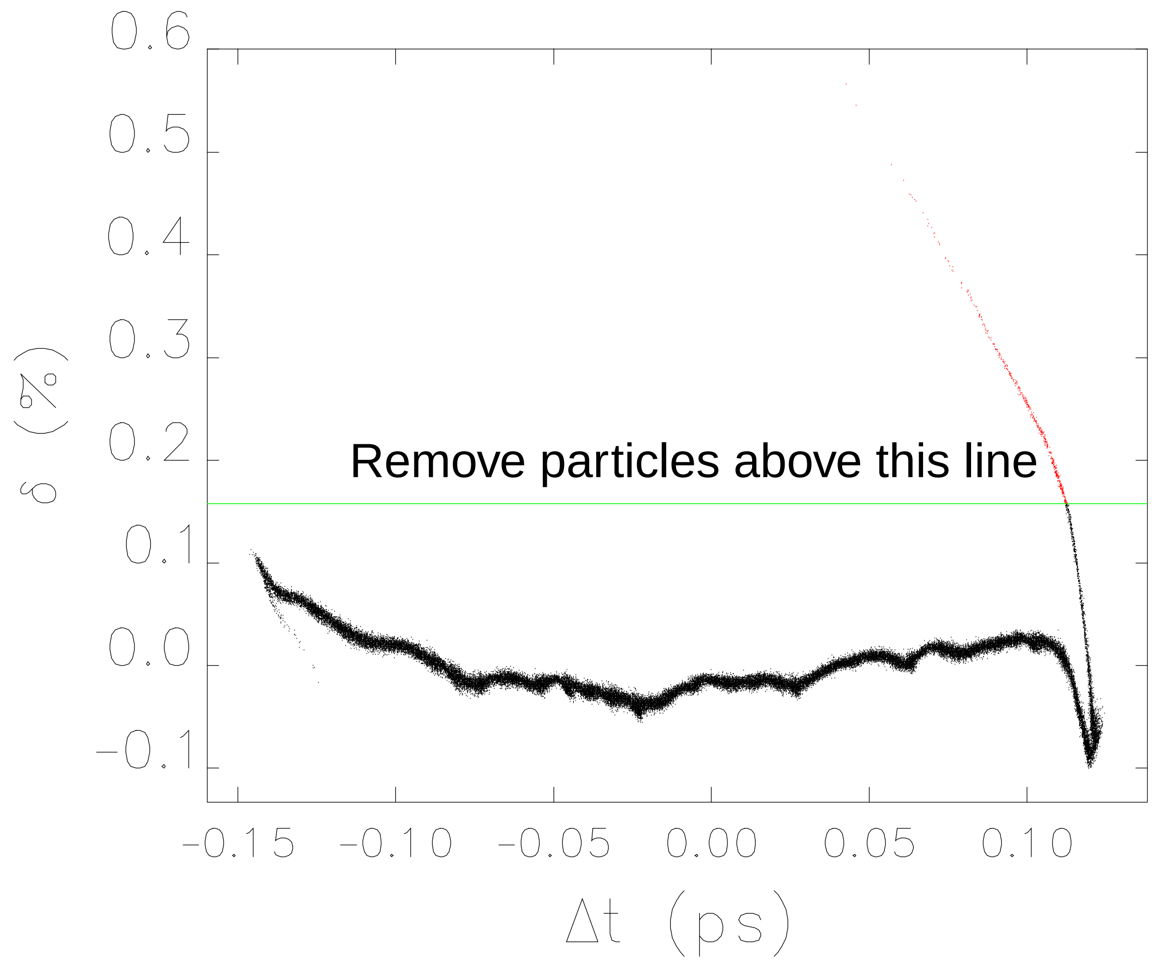

Calculational cut used in analysis

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Gain Length Stabiliity Requirement

- Assume a 5% (of 6.5m) RMS variation in gain length is allowed and assign half (in quadrature) to the accelerator (i.e., 3.5%)
- FEL model includes effects of 5 parameters: beam sizes, current, energy, and energy spread.
- In reality, 8 other beam moments are relevant: $\langle x \rangle$, $\langle y \rangle$, $\langle x' \rangle$, $\langle y' \rangle$, $\langle x'x \rangle$, $\langle y'y \rangle$, $\langle x'^2 \rangle$, and $\langle y'^2 \rangle$.
- Hence, using this FEL model we should allow only $3.5\sqrt{5/13}$%, or 2.2% (of 6.5m) RMS variation in gain length.
- Other parameters and the undulator are assigned the remainder of the 5% budget.

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Performance Constraints and Indicators

Quantity	**Limit (RMS Variation Except *)**
Constraints:	
slice gain length	2.2 % of 6.5m
beam energy	0.05 %
x centroid	1.8 μm
y centroid	1.4 μm
x’ centroid	0.08 μrad
y’ centroid	0.10 μrad
Indicators:	
total energy spread	<0.001 *
slice current	10 %
slice emittance	10 %
slice energy spread	10 %

- Slice quantities are averaged over central 80% of slices (“core slices”).

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Parameter Sweeps

- Various accelerator parameters were varied independently to assess the impact on performance.
- This is similar to analysis from LCLS Design Study Report (DSR) using a different code.
- Varied quantities:
  - Chicane power supplies.
  - Input beam charge, energy, timing, position, and slope.
  - RF phase and voltage (L1, L2, and L3).

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Comparison To Design Study Report —10% Current Change Criterion—

Quantity	DSR Limit	Limit From Sweeps
L1 phase	0.14 deg	0.14 deg
L2 phase	0.13 deg	0.15 deg
L3 phase	—	> 2 deg
L1 voltage	0.28 %	0.27 %
L2 voltage	0.52 %	0.48 %
L3 voltage	—	> 1 %
BC1 supply	0.24 %	0.10 %
BC2 supply 1	0.70 %	0.46 %
BC2 supply 2	4.80 %	2.8 %
gun timing	0.80 ps	0.71 ps
initial charge	2.9 %	3.2 %

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Limits From Sweeps Derived Using Performance Constraints

Quantity	DSR Limit	Limit From Sweeps	Limiting Constraint
L1 phase	0.14 deg	0.14 deg	gain length
L2 phase	0.13 deg	0.12 deg	gain length
L3 phase	—	2.2 deg	energy
L1 voltage	0.28 %	0.27 %	gain length
L2 voltage	0.52 %	0.15 %	energy
L3 voltage	—	0.073 %	energy
BC1 supply	0.24 %	0.10 %	gain length
BC2 supply 1	0.70 %	0.45 %	gain length
BC2 supply 2	4.80 %	2.7 %	gain length
gun timing	0.80 ps	0.32 ps	energy
initial charge	2.9 %	3.0 %	gain length
initial energy	—	0.18 %	gain length
initial x	—	7.6 μm	final x’
initial y	—	11 μm	final y
initial x’	—	1.1 μr	final x
initial y’	—	1.0 μr	final y’

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Jitter Simulations

- “Jitter” is anything not controlled by feedback.
- We assume the machine is tuned to operate at the design point.
- Simulated RF jitter reflects which klystron drives which sections.
- Three sets of 300-seed runs were done:
  1. No corrector errors or CSR.
  2. Corrector errors but no CSR.
  3. Corrector errors and CSR.
  4. Same as 2, but reduced errors 50% on x_o, y_o, x_o', y_o', Δt_o, and correctors.
- Use gaussian errors with 3-σ cutoff.

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Simulation Error Levels

Quantity	**RMS Jitter Level**
initial x, y centroid	20 μm (10% of size) *
initial x', y' centroid	1.78 μr (10% of divergence) *
initial t centroid	1 ps *
initial charge	2 %
initial energy	0.057 % (2 klystrons)
L1 phase	0.07 deg
L1 voltage	0.04 %
L2 phase	0.07 deg
L2 voltage	0.04 %
L3 phase	0.20 deg
L3 voltage	0.04 %
corrector strength	0.5 μT m (0.15 μrad at 1 GeV)

- These are realistic levels from P. Emma.
- Some levels (*) exceed individual values recommended by sweeps.

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What Was Left Out?

- Detailed jitter of photoinjector beam
  - second moments (e.g., beam size)
  - correlations among properties (e.g., energy with charge)
- Chicane dipoles—should be easy to make these very stable.
- Quadrupoles—presumably also very stable.

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Analysis of Jitter Results

- Determine RMS variation of performance measures.
- Determine percentage of shots inside the allowed limits for performance measures.
- Analyze correlations of jittered quantities with performance measures to find problem areas.
    - Correlation coefficient squared gives fraction of variation of performance measure, M, that is due to jittered quantity J:

$$r^2 = \frac{\langle MJ\rangle^2}{\langle M^2\rangle\langle J^2\rangle}$$

    - $r^2(1-P(r'>r))$ gives the fraction of the variation of M that is "probably" due to J.

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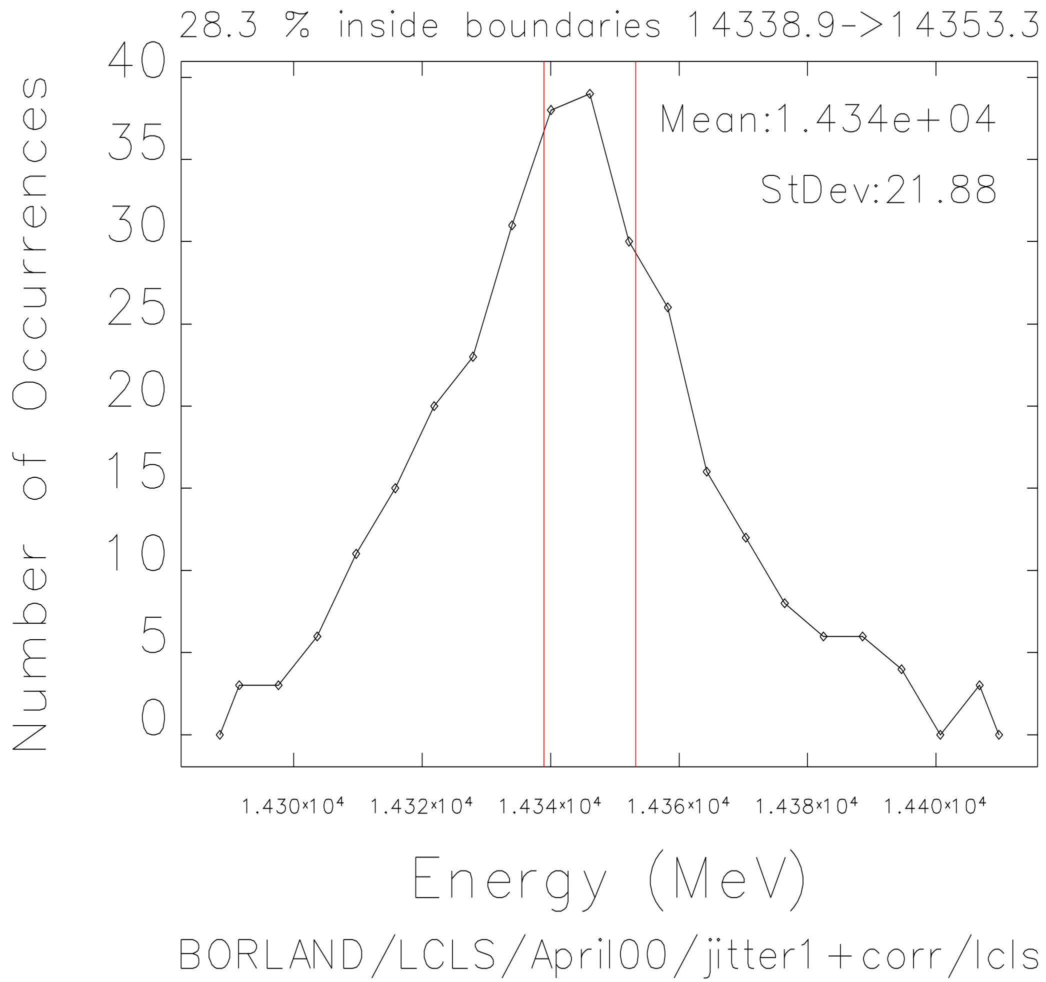
Sample Jitter Data—Set 2



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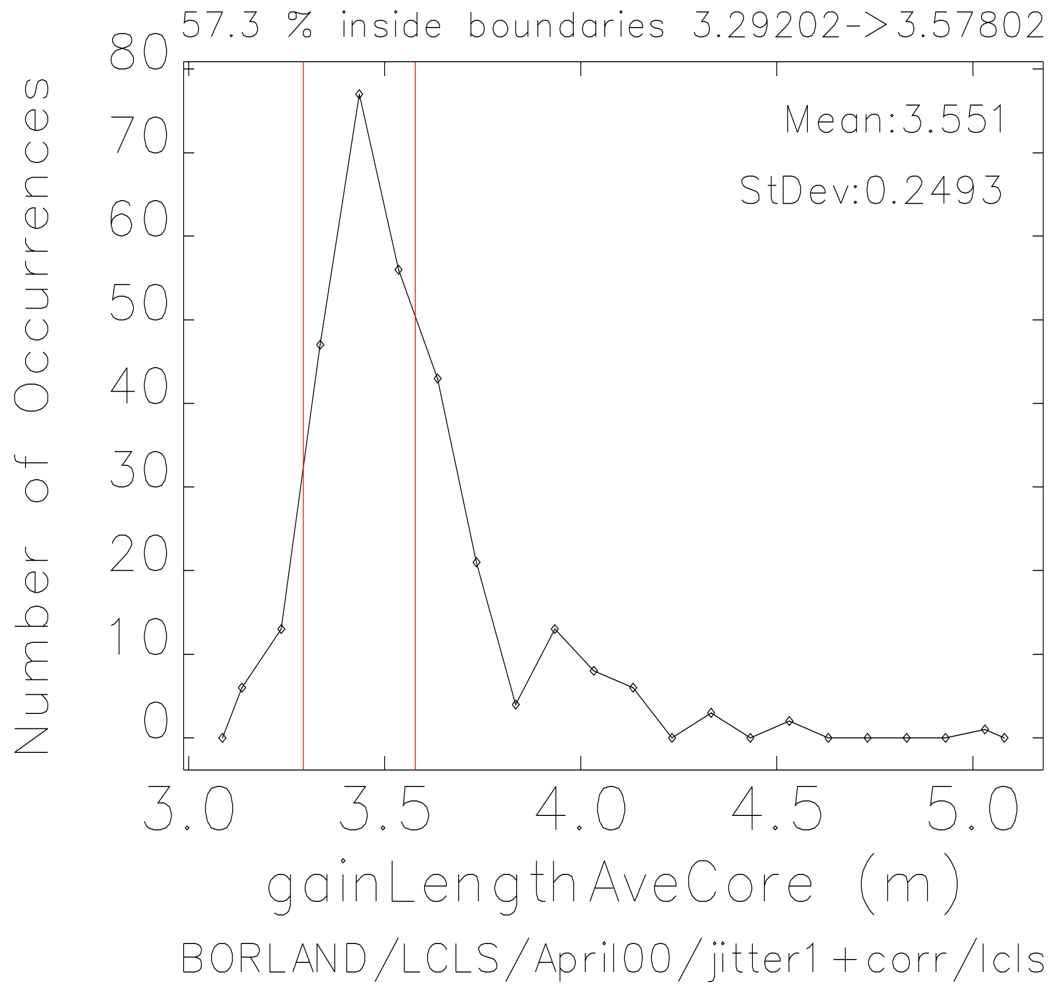

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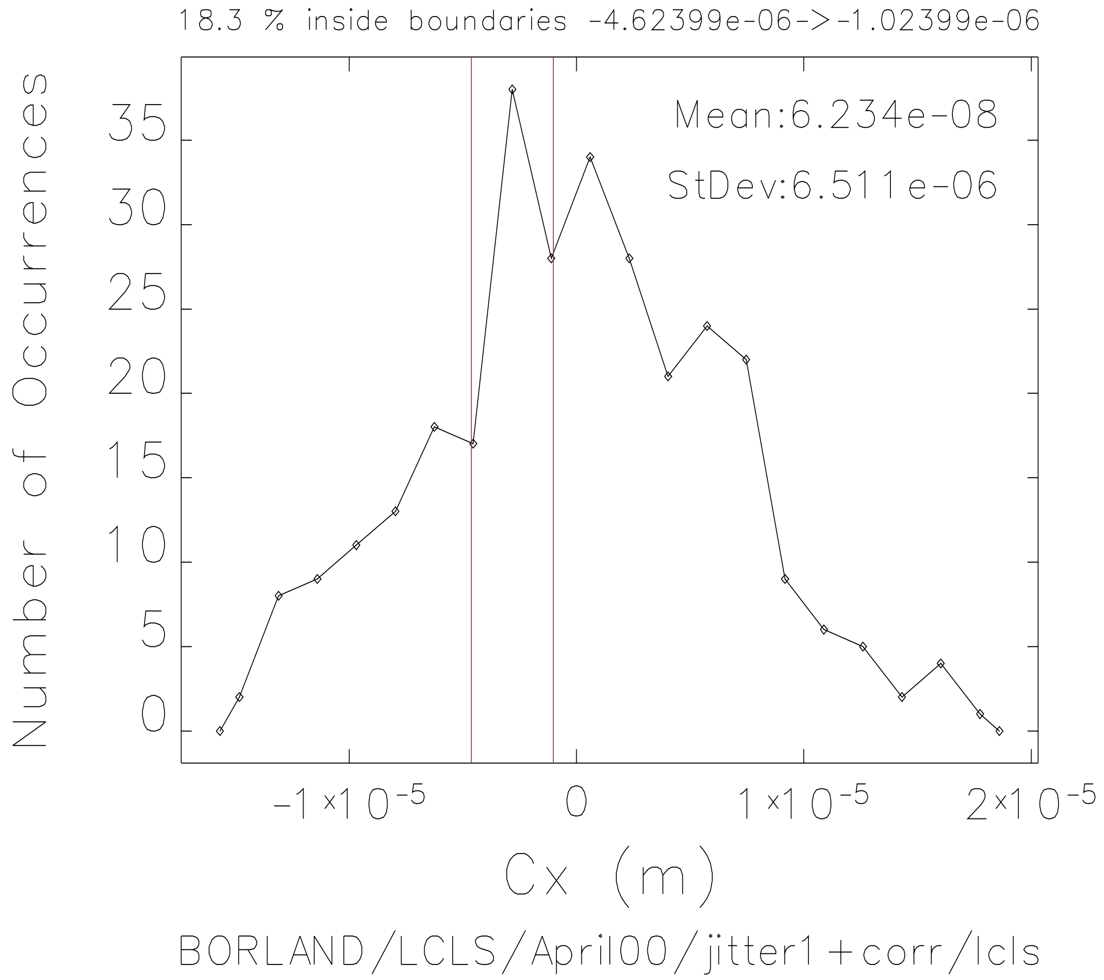

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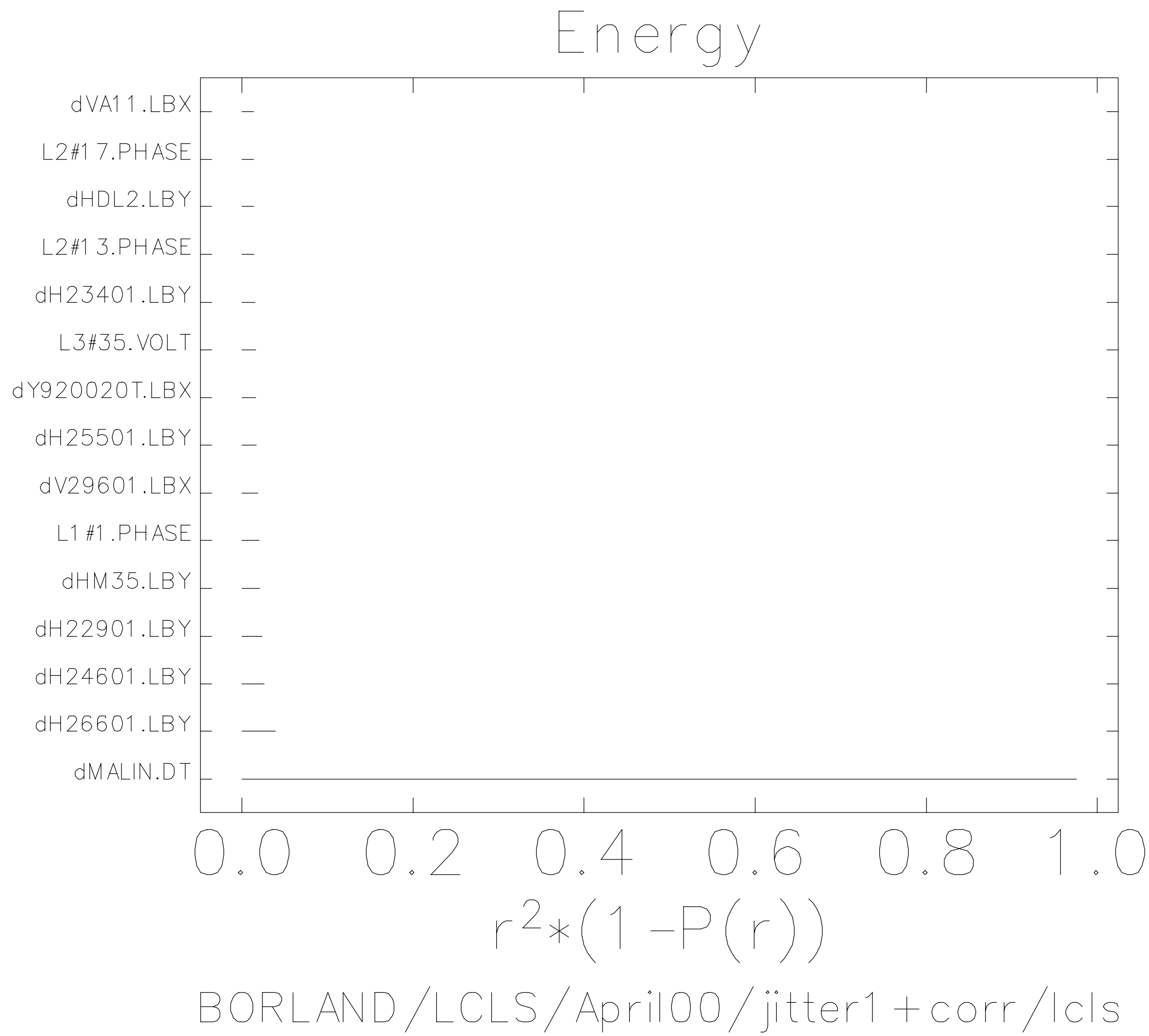
Sample Jitter Correlations—Set 2



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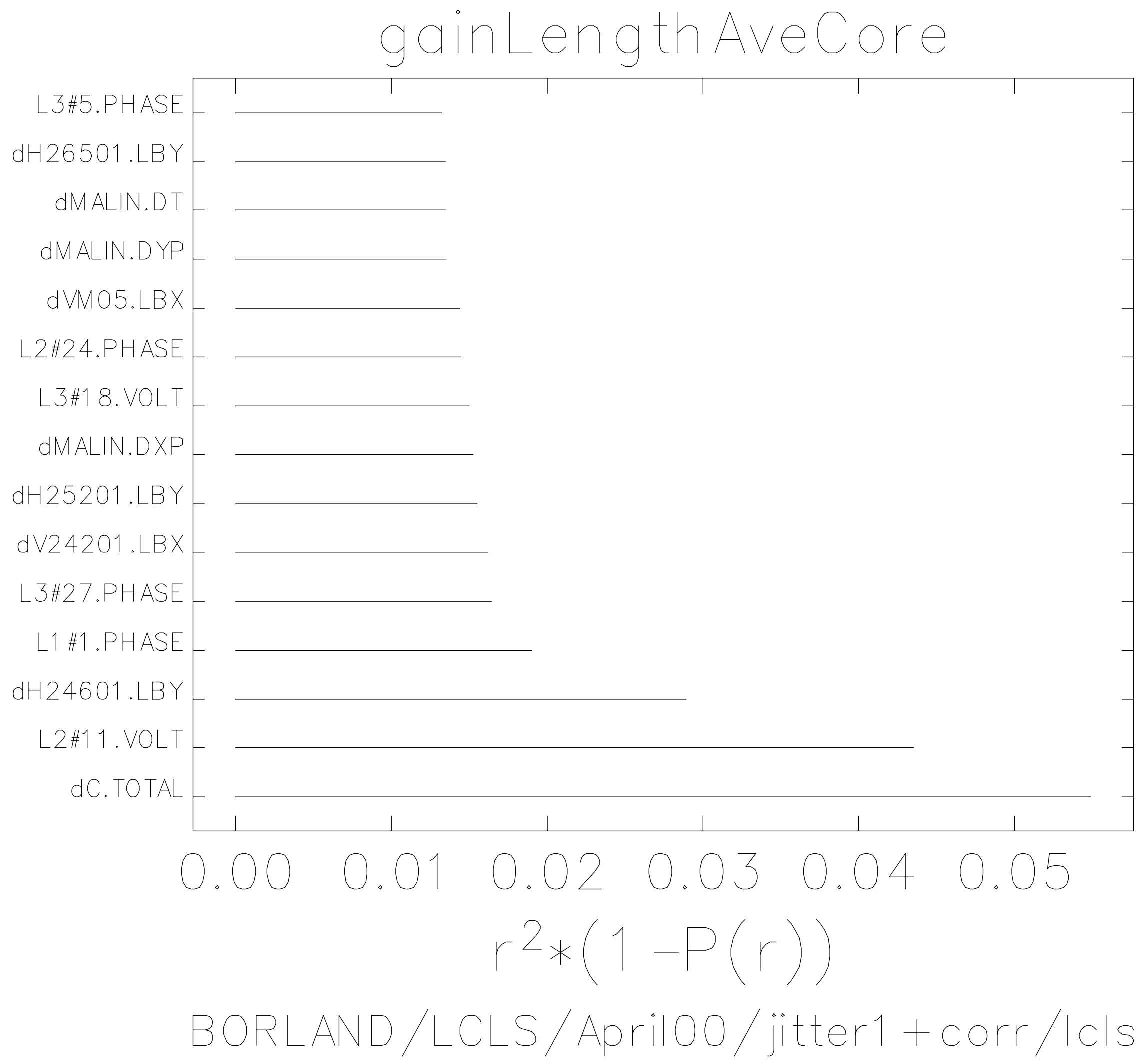

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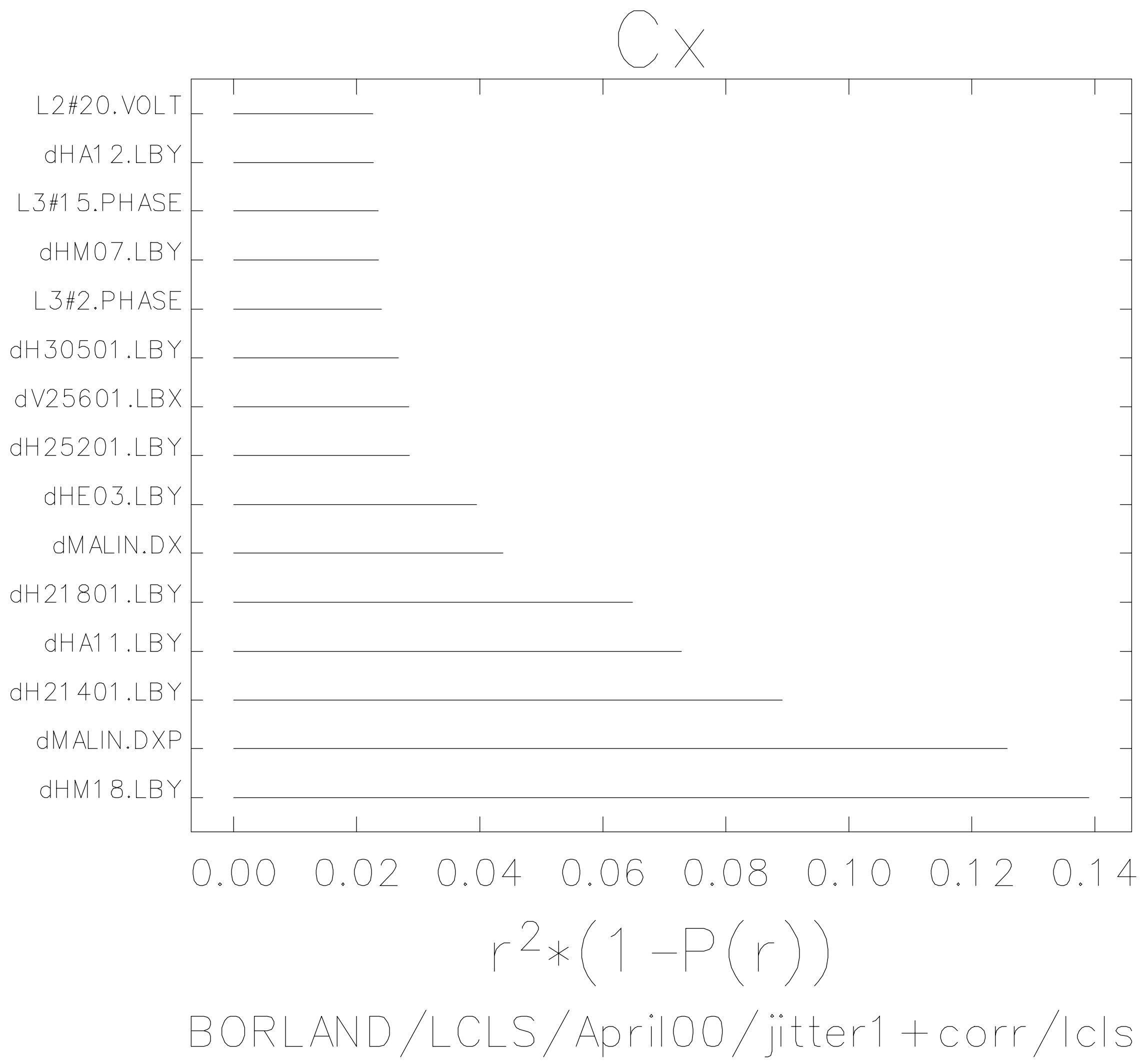
Sample Jitter Correlations—Set 2



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Summary of Jitter Results

Quantity ↓	**RMS Variation**				**Percentage Inside Window**				**Most Destructive Jitter Source**			
Set →	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
energy	0.14%	0.15%	0.15%	0.08%	31	28	25	44	Δt_o 97 %	Δt_o 97 %	Δt_o 97 %	Δt_o 89 %
gain length	5.9%	7.0%	5.8%	4.1%	54	57	57	62	Q_o 12 %	Q_o 5 %	Δt_o 29%	Q_o 28%
x centroid	3.5µm	6.5µm	8.3µm	3.3µm	36	18	18	41	x_o' 57 %	corr. 14 %	Q_o 16%	x_o' 14%
y centroid	2.8µm	4.9µm	5.0µm	2.4µm	38	25	23	43	y_o 76 %	y_o 25 %	y_o 26%	y_o 27%
x’ centroid	0.23µr	0.43µr	0.49µr	0.22µr	26	14	14	29	x_o 79 %	x_o 25 %	x_o 22%	x_o 30%
y’ centroid	0.22µr	0.48µr	0.46µr	0.22µr	35	18	16	30	y_o' 41 %	corr. 16 %	corr. 12%	corr. 16%

Sets:
1. no corrector jitter, no CSR
2. corrector jitter, no CSR
3. corrector jitter, CSR
4. same as 2, reduced errors 50% on x_o, y_o, x_o', y_o', Δt_o, and correctors.

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Problems and Possible Solutions

- The timing jitter requirement on the gun is extremely difficult because of the energy constraint.
  - Data gating based on pulse-by-pulse energy measurement may be the key.
- The centroid and gain length constraints are also difficult.
  - A longer undulator should help.

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Extension of Jitter Simulations

- Extension of the simulations to cover the full system is advisable.
- Photoinjector
  - Tolerance studies and randomized simulations are needed.
  - Will cover possibility of correlations among photoinjector output parameters.
  - PARMELA ?
- FEL
  - Effect of slice-by-slice beta match through undulator.
  - Effect of trajectory jitter.
  - RON code may be adapted to this.

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LEUTL Connection

- LEUTL has much in common with LCLS
  - Very similar PC gun laser system.
  - Multiple SLEDed SLAC-type structures.
  - Flexible bunch compressor (July 2000).
  - Separated function undulator cell design.
  - Tolerance levels are similar, according to simulations with **elegant**.
- LEUTL has been driven by a thermionic rf gun which showed greater stability than the PC gun.
- LEUTL is heavily instrumented along the length of the undulator.